

Development and Test of Combustion Chamber for Stirling Engine Heated by Natural Gas

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The combustion chamber is an important component for the Stirling engine heated by natural gas. In the paper, we develop a combustion chamber for the Stirling engine which aims to generate 3~5 kW_e electric power. The combustion chamber includes three main components: combustion module, heat exchange cavity and thermal head. Its feature is that the structure can divide “combustion” process and “heat transfer” process into two apparent individual steps and make them happen one by one. Since natural gas can mix with air fully before burning, the combustion process can be easily completed without the second wind. The flame can avoid contacting the thermal head of Stirling engine, and the temperature fields can be easily controlled. The designed combustion chamber is manufactured and its performance is tested by an experiment which includes two steps. The experimental result of the first step proves that the mixture of air and natural gas can be easily ignited and the flame burns stably. In the second step of experiment, the combustion heat flux can reach 20 kW, and the energy utilization efficiency of thermal head has exceeded 0.5. These test results show that the thermal performance of combustion chamber has reached the design goal. The designed combustion chamber can be applied to a real Stirling engine heated by natural gas which is to generate 3~5 kW_e electric power.

Keywords: Combustion Chamber; Natural Gas; Stirling Engine; Designing; Performance Test

Introduction

There are two apparent advantages in the distributed energy systems which use natural gas as heat source: 1. less contaminants are emitted during the working process, because the main products of natural gas combustion process are H₂O and CO₂; 2. The reserves of natural gas are abundant on the earth, and can be used in a longer time than petroleum and coal. The Stirling engine is one kind of engines which are externally heated and can be easily driven by natural gas combustion. The systems used with Stirling engine and driven by natural gas have already appeared, just like Cleanergy's V-161 Stirling

engine CHP (Combined Heat and Power) system and so on [1-5]. The Stirling engine CHP system would be widely applied due to its characters of low noise, long maintenance cycle and high reliability [6-7].

In the Stirling engine CHP system driven by natural gas mentioned above, the combustion chamber is a key component, because the combustion performance is directly related to the life of heater and the performance of Stirling engine [8]. Actually, the combustion chambers can be divided into two types according to the mixing way of air and natural gas: one type is the diffusion combustion chamber and the other type is the premixing combustion chamber. As we know, most Stirling engines

use diffusion combustion chamber because of its simple structure. And the processes of combustion and heat transfer happen in the same space. Although the diffusion combustion chamber has a relatively simple structure and low cost, the flame is so long that it may instantaneously overheat the heater tubes of Stirling engine. In addition, the second wind is needed to ensure the combustion process can be nearly completed. So it is not easy to control the temperature around the wall of heater tubes. If the combustion chamber is a fully premixing structure, the combustion efficiency will be higher and the flame will be shorter, but the manufacturing cost must be higher because of the complicated premixing structure, and the temperature around the wall of heater tubes is still not easy to be controlled.

In this paper, we aim to develop a combustion chamber for Stirling engine which uses natural gas as heat source. We try to design a combustion chamber which has advantages of both diffusion and premixing. The combustion chamber has a feature that air and natural gas mixed before they are burned. The thermal performance of combustion chamber is tested by an experiment which includes two steps. In the experiment, we will find whether the combustion process can be easily completed without the second wind and the flame can avoid contacting thermal head. The designed combustion chamber aims to be applied to Stirling engine which can generate 3~5 kW_e electric power.

Design of Combustion Chamber

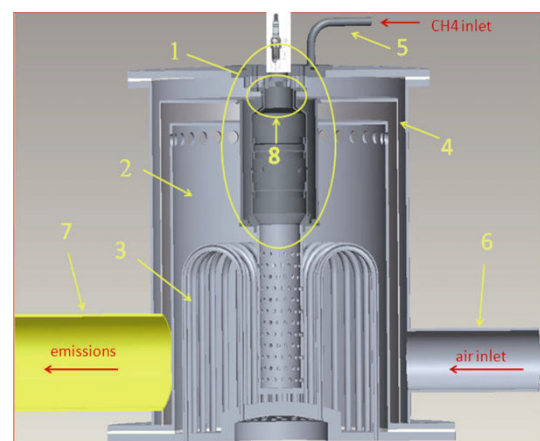
In fact, there are two processes that actually happen in combustion chamber of Stirling engine: the fuels combust and heat transfers at the heater tubes of Stirling engine. We can call two processes “combustion” and “heat transfer” separately for short. In some diffusion combustion chambers which are already used for Cleanergy’s V-161 and STM’s 4-120 Stirling engines, the “combustion” process and the “heat transfer” process actually happen simultaneously in the same space [9-11], so that the flame may contact heater tubes, the hot spots can appear on the wall of heater tubes at any time, and the temperature is hard to control around the heater tubes of Stirling engine in the combustion chamber. So if we can divide the “combustion” process and “heat transfer” process into two apparent steps and make them happen one by one, the flame may avoid contacting the heater tubes so that the hot spot can’t appear, and the temperature across combustion chamber can be easily controlled. This is our designing concept to develop the combustion chamber.

The combustion chamber that we design for Stirling engine which is heated by natural gas includes three main

parts: combustion module, heat exchange cavity and thermal head of Stirling engine. The “combustion” process mentioned above happens only in combustion module completely. After combustion the hot waste gas sprays into heat exchange cavity to heat thermal head of Stirling engine in a closed space which is made up of heat exchange cavity and thermal head of Stirling engine, so the “heat transfer” process mentioned above can only happen here. The structure can realize our design idea which is to divide the “combustion” process and “heat transfer” process into two apparent steps and make them happen one by one. The details of the design will be described below.

We design the structure as shown in Fig. 1. The combustion module is assembled on the top of heat exchange cavity, and the thermal head of Stirling engine is assembled at the bottom of heat exchange cavity. There is also an air preheating layer in heat exchange cavity. The combustion module includes a natural gas inlet tube and a spark plug (Fig. 2a) which is used to ignite air and natural gas mixture. At the bottom of swirler there are eight nozzle holes, from which natural gas sprays into their corresponding swirler channels (Fig. 2b).

The swirler is the key part to hold the flame stable. The film holes in the wall of flame tube (Fig. 2e) can generate air films to cool the wall of flame tube. The air mixing holes allow some unburned air to mix into the waste gas generated after burning, to let the temperature of waste gas down to 900~1000°C, and then hot waste gas sprays out of flame tube from corn holes into heat exchange cavity (Fig. 2c). The air inlet channel and emission channel can be seen on the external shell of combustion chamber (Fig. 2d). The thermal head of Stirling engine is mainly made up of 36 U-type heater tubes



1-Combustion module; 2-Heat exchange cavity; 3-Heater tubes of the Stirling engine; 4-Air preheating layer; 5-Natural gas inlet tube; 6-Air inlet channel; 7-Emissions channel; 8- Ignition location

Fig. 1 The structure of designed combustion chamber for Stirling engine heated by natural gas.

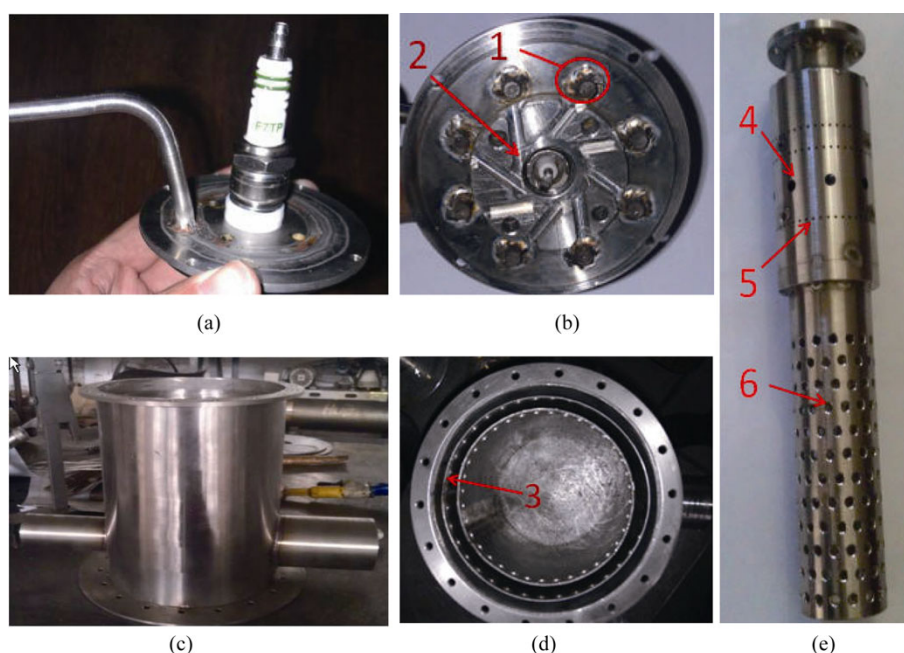


Fig. 2 Some key parts of the machined combustion chamber. (a) Spark plug and natural gas inlet tube; (b) Swirler; 1-nozzle holes; 2-swirler channel; (c) Heat exchange cavity; 3-air pre-heating layer; (d) Outside shell of the combustion chamber (e) Flame tube; 4-film holes; 5-air mixing holes; 6-corn holes

and a stainless steel cover, and it is enough for the thermal performance test of combustion chamber although the structure of this thermal head is simpler than that used on the real Stirling engine.

The main working process of the designed combustion chamber is shown in Fig. 3. The fresh air and natural gas flow into the combustion chamber from their separate channels, and mix in the short swirler channels. Then the spark plug ignites the mixture at the ignition location as shown in Fig. 1. Some unburned fresh air mixes into the waste gas generated after burning to let the temperature

down, and then the hot waste gas sprays out from the corn holes to heat the heater tubes of Stirling engine. After heat exchanging, the waste gas flows out of combustion chamber from the inside of preheating layer to the emission channel, so that the fresh air can be preheated when it flows across the outside of preheating layer before it mixes with natural gas. The waste gas finally emits out and the working process ends.

Our design goal is that the combustion chamber can generate 20 kW energy power, which is used to heat Stirling engine to generate 3~5 kW_e electric power. The designed thermal parameters are listed in Table 1. In order to adjust the working condition easily in the experimental operation, the parameters are designed in not a number but a range. The air to natural gas ratio changes only in a small range, and this is the regulation to obey during the process of adjusting flow rate. The temperature of waste gas that flows into the heat exchange cavity is designed at about 900 °C which is a suitable temperature to heat

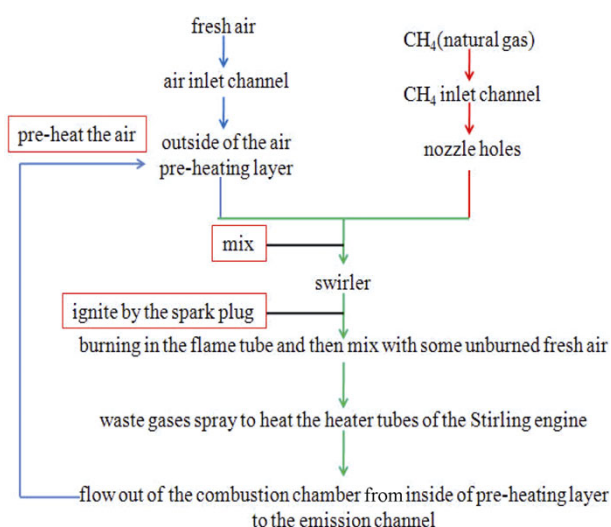


Fig. 3 Main working process of the designed combustion chamber

Table 1 Thermal designing parameters

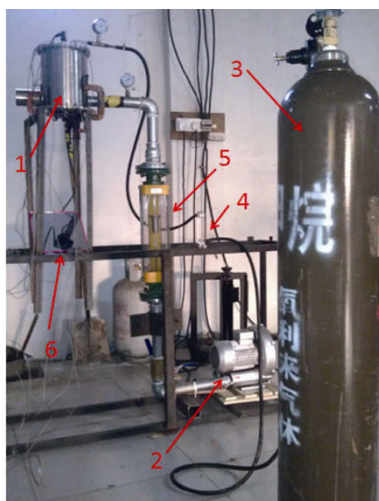
Parameters	Value
Inlet air flow rate (g/s)	12~24
Inlet air pressure (kPa)	103~110
Inlet air temperature (°C)	0~50
Inlet natural gas flow rate (g/s)	0.25~0.55
Inlet natural gas pressure (kPa)	130~203
Inlet natural gas temperature (°C)	0~50
Air to natural gas flow ratio (-)	45~50

the Stirling engine. The temperature of final emission is designed at about 300 °C when it flows out of the combustion chamber.

Thermal Performance Test of Designed Combustion Chamber

We test the performance of the designed combustion chamber by an experiment which includes two steps. The first step of the experiment is to check the combustion condition. If the combustion process is stable and no flame sprays out of the flame tube and the corn holes, we can ensure that the “combustion” process and “heat transfer” process are indeed separate. The second step experiment is based on the first step. In this step experiment, the utilized thermal energy and working efficiencies are evaluated in the combustion process.

The test system used for the first step experiment is shown in Fig. 4. The air is blown into system tubes by a whirlpool pump, and the maximum air flow rate generated by it is around 80 m³/h at 20 °C and 1 atm. Natural gas is supplied by a high-pressure bottle, in which the purity of CH₄ is 99%. There are an air flowmeter and a natural gas flowmeter to measure the flow rates of air and natural gas across their separate tubes. In order to observe the flame directly, the heater tubes of Stirling engine is not assembled in the first step experiment. Instead, a stainless steel cover with a quartz glass in its center as a porthole is assembled at the bottom of combustion chamber. A mirror is placed under the combustion chamber to comfortably observe the combustion phenomenon that happens in the closed cavity. The view seen from the mirror before combustion is shown in Fig. 5a.



1-designed combustion chamber; 2-air blower; 3-natural gas source; 4-natural gas flowmeter; 5-air flowmeter; 6-mirror

Fig. 4 The first experimental system

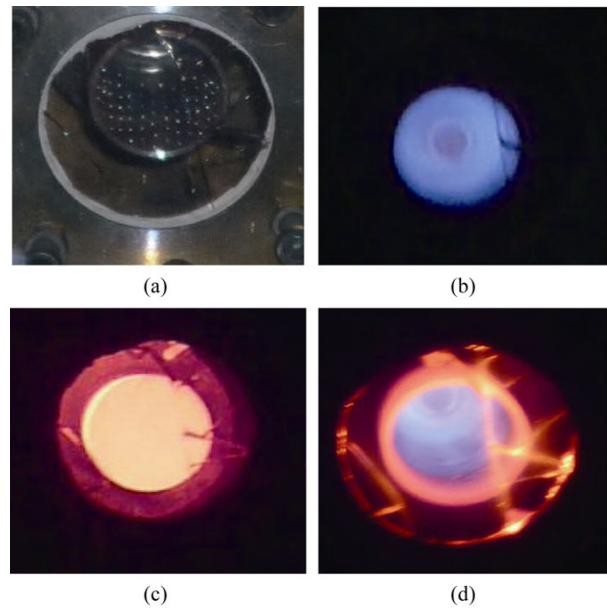


Fig. 5 Phenomena during the first experiment, (a) observation view before combustion (b) observation view when the hot waste gas is 380~450 °C; (c) observation view when the hot waste gas is 850~910 °C; (d) observation view after the bottom of the flame tube is sealed

During the first step experiment, we find the mixture of air and natural gas can be easily ignited when the flow rates of air and natural gas are 40~45 m³/h and 15~16 L/min respectively. The combustion process is stable. The flame is shown in Fig. 5b. The temperature of hot waste gas obtained by the thermocouples in the heat exchange cavity is between 380 and 450 °C. The flow rate of air increases as that of natural gas increases, and the temperature in the cavity is higher and higher. Finally, we manage to control the temperature of hot waste gas up to 910 °C, and the view of that moment is shown in Fig. 5c (We can also see the quartz glass is cracked because of the high thermal stress.). We seal the bottom of flame tube after we ensure the mixture of air and natural gas can be easily ignited and the flame is stable in the combustion chamber. Then we observe whether the flame sprays out of corn holes. The view is shown in Fig. 5d as a result, and no flame sprays out of corn holes indeed. This result means that the flame can be burning in the flame tube completely and stably in the combustion module, and we achieve that the “combustion” process and “heat transfer” process are separate.

The system for the second step experiment is shown in Fig. 6. We remove the stainless steel cover at the bottom of combustion chamber, and assemble the thermal head of Stirling engine for this experiment instead. The thermal head only composes of 36 U-type heater tubes and some closed rooms for water flowing across them. We plan to use water to measure how much energy can be

used for the Stirling engine, so there are an inlet and an outlet for the water at the bottom of thermal head. Compared to the system for the first step, we also add a water flowmeter and some water channels. We have wrapped up a mineral wool insulation layer about 40 mm thickness outside of the combustion chamber before this step experiment starts.

The second step experiment is done based on the operation conditions obtained from the first step experiment, and the results are listed in Table 2. All of these 4 typical



Fig. 6 The second experimental system

Table 2 Results of the performance test

Experimental parameters	Row 1	Row 2	Row 3	Row 4
Inlet air flow rate (g/s)	14.4	18.6	18.3	13.1
Inlet air pressure (kPa)	103	103	103	103
Inlet air temperature (°C)	30.7	40.2	36.1	42.9
Pre-heated air temperature (°C)	55.0	84.6	81.3	96.7
Outlet waste gas temperature (°C)	209	225	267	250
Inlet natural gas flow rate (g/s)	0.321	0.341	0.402	0.281
Inlet natural gas pressure (kPa)	134	144	153	131
Inlet natural gas temperature (°C)	16.2	16.4	17.3	17.4
Air to natural gas flow ratio(-)	44.8	54.7	45.6	46.6
Water flow rate (kg/h)	790	923	610	605
Inlet water temperature (°C)	38.1	13.8	14.2	14.2
Outlet water temperature (°C)	46.0	23.1	29.3	26.7
Parameters to evaluate energy utilization performance				
CH ₄ complete combustion heat (kW)	16.1	17.1	20.1	14.1
Heat quantity absorbed by water (kW)	7.26	9.90	10.7	8.83
Heat quantity absorbed by air (kW)	2.58	3.48	4.29	2.73
Combustion efficiency	0.61	0.78	0.74	0.82
Energy utilization efficiency of the heat head	0.45	0.58	0.53	0.63
Parameters to evaluate preheating performance				
Usable energy in the emissions (kW)	3.73	4.84	5.99	4.00
Preheating quantity absorbed by fresh air (kW)	0.249	0.591	0.591	0.503
Heat reclaim efficiency	0.07	0.12	0.10	0.13

rows of experimental test data are recorded at relative stable conditions. In Table 2, the experimental parameters are recorded directly by different instruments. The parameters to evaluate energy utilization and preheating performance of the combustion chamber are computed based on the experimental parameters. Among them, we define

$$\begin{aligned} \text{Combustion efficiency} &= \frac{\text{Heat quantity absorbed by water} + \text{Heat quantity absorbed by air}}{\text{CH}_4 \text{ complete combustion heat}} \\ \text{Energy utilization efficiency of thermal head} &= \frac{\text{Heat quantity absorbed by water}}{\text{CH}_4 \text{ complete combustion heat}} \\ \text{Heat reclaim efficiency} &= \frac{\text{Preheating quantity absorbed by fresh air}}{\text{Usable energy in the emissions}} \end{aligned}$$

Discussions

The combustion process can be stably running at multiple working conditions. Typical working conditions are shown in Table 2. When combustion is running normally, the pressure of air blown into the combustion chamber is 1 atm while the pressure of natural gas is a little higher than 1 atm, so the work to drive air and natural gas into the combustion chamber can be easier. The combustion process can start at half of the maximum designed loads condition at any time. From the data listed in Table 2, the maximum natural gas complete combustion heat is up to 20 kW, which is our design goal, though it has not reached its maximum combustion load compared to the design parameters listed in Table 1. The combustion efficiency can reach upon 0.7 and the energy utilization efficiency of thermal head can reach upon 0.5 as shown in row 2~4 of Table 2. The heat reclaim efficiency is not high because the air pre-heater is made of a stainless steel layer, but it still works and can reclaim about 10% heat quantity from the usable energy in the emissions. During the experiments, the temperature rise of water is controlled at about 10 °C, so that the temperature in combustion chamber for the experiment is not as high as that for a real Stirling engine. The combustion efficiency and energy utilization efficiency may be a little higher in the experiments than those at the conditions of the real Stirling engine running, but the results obtained from experimental test can still be used to evaluate the performance of combustion chamber and can be regarded as the reference for an equipment applied to the real Stirling engine.

Conclusions

In the paper, we develop a combustion chamber for the Stirling engine heated by natural gas. The combustion

chamber has the structure that can divide the “combustion” and “heat transfer” process into two apparent steps and make them happen one by one, so the flame can avoid contacting the thermal head of Stirling engine and the temperature fields across the combustion chamber can be easily controlled. There are short channels for air and natural gas premixed in the swirler before they are ignited. The combustion process can be easily completed without the second wind. The flame is stable and short. The phenomena viewed in the first step experiment as shown in Fig. 2 prove the above statements.

The combustion heat can reach 20 kW, and the energy utilization efficiency of thermal head has exceeded 0.5 according to the test results listed in Table 2. The heat reclaim efficiency can be higher by improving the preheating structure instead of the air preheating layer, but the structure may be complicated and the cost must be higher. The designed combustion chamber can be easily machined, and can be applied to a real Stirling engine which aims to generate 3–5 kW_e electric power heated by natural gas.

Acknowledgements

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